Wellhead Protection Plan

Part I

Wellhead Protection Area Delineation
Drinking Water Supply Management Area Delineation
Well and Aquifer Vulnerability Assessment

For

The City of Taconite

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Glossary of Terms

Capture Zone. The subsurface area surrounding a well or well field that supplies a public water supply system through which water is likely to move toward and reach the well. The capture zone and the surface water contribution area, when needed, comprise the wellhead protection area (WHPA).

Drinking Water Supply Management Area (DWSMA). The area delineated using identifiable land marks, defined in this report, that reflects the scientifically calculated wellhead protection area boundaries as closely as possible (Minnesota Rules 4720.5100, subpart 13).

Source Water Protection Area (SWPA). A source water assessment includes a description of 1) the area to be protected, 2) potential contamination sources that may impact the source of drinking water, and 3) the susceptibility of the public water supply to potential contamination sources. For the purposes of this delineation report, the SWPA and the DWSMA are the same.

Wellhead Protection Area (WHPA). The surface and subsurface area surrounding a well or well field that supplies a public water system, through which contaminants are likely to move toward and reach the well or well field (Minnesota Statutes, Part 103I.005, subdivision 24).

Introduction

This report documents the technical information necessary to prepare Part I of a wellhead protection plan that will help ensure an adequate and safe drinking water supply for the city of Taconite, public water supply identification number 1310028. It documents the delineation of the wellhead protection area (WHPA), the drinking water supply management area (DWSMA), and the vulnerability assessments for the public water supply wells and DWSMA. An updated source water assessment with a new protection area (SWPA) also is included. Definitions explaining the differences between the terms WHPA, DWSMA, and SWPA are provided in the "Glossary of Terms" at the beginning of this report

The delineation was performed in accordance with Minnesota Rules 4720.5100-4720.5590 for preparing and implementing wellhead protection plans for public water supply wells. The Minnesota Department of Health (MDH) administers these rules and the results described in this report reflect those of the MDH to 1) identify the capture zones for delineation of the WHPA, and 2) prepare well and DWSMA vulnerability assessments. Also, this report presents the findings of the public water supplier to identify the boundaries of the DWSMA.

The public water supplier operates two wells, termed Well No. 1 (Unique No. 241489) and Well No. 2 (Unique No. 495997). The wells are located in Section 27 of Township 56 North, Range 24 West in Itasca County. Appendix I contains Table 1 that presents some of the key information about these wells that affect their vulnerability assessments.

The WHPA for Wells No. 1 and 2 (241489 and 495997) was determined using a modified volumetric analysis recommended by the MDH for fractured rock aquifers (MDH, 2005). The DWSMA boundaries were determined using U.S. Public Land Survey boundaries, city streets, and roads. Figure 1 shows the boundaries for the WHPA and the DWSMA.

Source Water Assessment

The MDH is required under Section 1453 of the 1996 Amendments to the federal Safe Drinking Water Act to prepare source water assessments for all public water supply systems. Congress intends that assessments should be used to educate public water suppliers and the customers they serve about the source of their drinking water and potential contaminants that may affect people's health. The following Source Water Assessment for the public water supplier contains the information specified in Minnesota's source water assessment program description.

Source Water Assessment for
The City of Taconite

Public Water Supplier ID Number: 1310028

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Status of the Source Water Protection Plan –

The Minnesota Department of Health has approved the 1) delineation of the wellhead protection area, 2) delineation of the drinking water supply management area, and 3) assessments of well and aquifer vulnerability. The public water supplier is proceeding with the development of the remainder of the wellhead protection plan.

Source Water Protection Area - See Figure 1.

Description of the Source Water - The water supply for the city of Taconite comes from the Biwabik Iron Formation, a bedrock aquifer that exhibits confined hydraulic conditions at the city wells. The aquifer is about 500 feet thick and is locally covered by approximately 100 feet of overlying bedrock of the Virginia Formation, a thin layer of Cretaceous sedimentary rocks, and approximately 170 feet of glacial sediments. Generally, groundwater moves in a northwesterly direction in the wellhead protection area, although the flow directions are likely variable and influenced by the water level within the Canisteo Mine Pit.

Table 2
Wells Used by the Public Water Supplier

Well No.	Unique No.	Well Use	Aquifer Type	Well Depth (ft)	Well Sensitivity	Aquifer Sensitivity
1	241489	Primary	Biwabik Iron Formation	384	High	Moderate
2	495997	Primary	Biwabik Iron Formation	394	Low	Moderate

Aquifer Sensitivity - The sensitivity of the aquifer used by the public water supplier is moderate throughout the drinking water supply management area. This rating reflects that the aquifer is covered by permeably low bedrock and glacial deposits, but young water is present in the aquifer. Tritium samples taken from Wells 1 and 2 (241489 and 495997) on September 4, 1991, and February 9, 2004, showed 20.1 and 19.7 tritium units, indicating that most of the water pumped by the wells entered the ground within the last 50 years.

Well Construction Assessment - Existing construction information for Well 1 (241489) suggests that grout was not drawn into the annular space of the outer well casing as it was driven, as is currently required by the State Well Code. In addition, the inner well casing is telescoped – in other words, it does not extend above the ground surface as required by code. Finally, it is unclear whether the annular space between the outer and inner well casings is grouted. These factors could provide pathways for near-surface contamination to enter the source water.

Susceptibility of the Source Water to Contamination - The source water used by the public water supplier is considered susceptible to potential sources of contamination principally because of the geologic setting, although the construction of Well 1 (241489) may also provide an avenue for contamination. The land uses within the drinking water supply management area may potentially contribute contaminants that may present a health concern to the users of the public water supply.

Contaminants of Concern - Routine testing of water from the Taconite city wells has shown that it has generally been free from contaminants and meets all standards of the Safe Drinking Water Act. However, the wells are considered susceptible to contamination from a variety of sources. These include contaminants that may persist in groundwater for long periods of time and which are not susceptible to retardation or removal by movement through fine-grained sediment.

Delineation of the Wellhead Protection Area

Physical Setting

The City of Taconite is located in Itasca County near the western end of the Mesabi Iron Range. The town is surrounded by features associated with a nearly 100-year old history of iron mining, which ceased in this area in the mid-1980s (Jones, 2002). These features include tailings ponds, waste rock stockpiles, and, most prominently, the Canisteo Mine Pit lake (Figure 2). The Canisteo Mine Pit lake is situated approximately 2,400 feet north of Well 1 (228834). It has an average depth of approximately 100 feet, but is up to 300 feet in depth locally. It is nearly five miles in length, averages approximately 0.5 miles in width, and was created when water levels rose following the cessation of mining at a series of closely-spaced, abandoned natural ore mine pits.

Assessment of Data Elements

This section documents how the data elements specified under Minnesota Rules 4720.5400 were used to describe the physical environment.

Soils: The aquifer used by the city of Taconite is buried beneath younger bedrock and glacial deposits, except where exposed at the margins of the Canisteo Mine Pit lake. As a result, soils maps are not useful for delineating its boundaries. However, the Itasca County soils survey (Nyberg, 1987) was useful for assessing the vulnerability of the aquifer.

Precipitation: The method used to delineate the WHPA does not account for aquifer recharge. As a result, precipitation was not considered.

Geology: Figures 2, 3 and 4 show the distribution of the aquifer and its stratigraphic relationships with adjacent geologic materials. They were prepared using existing geologic maps (Jennings and Reynolds, 2005, and Jirsa and others, 2005) and well record data that is contained in the County Well Index database. A complete listing of the geological maps and studies that were used to further define local hydrogeologic conditions is provided in the section of this report entitled "Selected References."

The natural landscape of the Taconite area was strongly affected by late-Pleistocene glaciation. Although the town of Taconite is situated on relatively flat ground, the surrounding area consists of an irregular topography of small hills and depressions (Figure 2). This distribution of landforms is attributed to rapidly shifting depositional environments commonly found near the margins of glacial ice, probably of the Koochiching lobe (Jennings and Reynolds, 2005). Dominant glacial landforms in the Taconite area include Trout Lake and Holman Lake, both attributed to a subglacial drainage feature known as a tunnel valley, and the irregular hills adjacent to and west of Trout Lake, indicative of ice contact deposits (Jennings and Reynolds, 2005).

Although surficial materials in the Taconite area are dominated by sediments of the Koochiching lobe, interpretations are complicated by apparent admixture with sediments of the Rainy lobe, probably owing to collapse of both units related to late melting of buried ice (Jennings and Reynolds, 2005). The total thickness of glacial sediments in the Taconite area is on the order of

170 feet. Generally, drift thickens to the south and thins to the north, approaching zero along the crest of the Giants Range, a linear ridge composed of Archean granitic and metasedimentary rocks that trends northeast to southwest that is located north of the Canisteo Mine Pit (Jones, 2002).

Winter (1971) identified three major morainal till units and associated glaciofluvial outwash deposits in this general area, only two of which appear to occur in Taconite. These are the upper surficial and middle boulder till units (Jones, 2002). The surficial till is brown in color, sandy, silty, and calcareous, and is generally less than 30 feet thick in this area (Jones, 2002). The boulder till ranges widely in color from gray to yellow, and consists of sands and silts, with abundant cobbles and boulders (Winter, 1971). Glaciofluvial outwash deposits lie stratigraphically between the surficial and boulder tills, and often lie between the boulder till and deeper tills or bedrock (Winter, 1973a). Those that occur between the surficial and boulder tills are the thickest and most continuous outwash deposits in the Taconite area. They are often greater than 50 feet thick and sometimes greater than 100 feet in portions of buried valleys (Winter, 1973a). These outwash deposits consist of fine-grained sands throughout much of the study area. However, they are highly transmissive, coarse-grained sands, gravels and boulders occurring within buried valleys and at other locations where the bedrock surface is low (Jones, 2002). The Taconite city wells appear to be located in such a bedrock low, based on the mapping of Jirsa and others (2005).

The bedrock geology of the Taconite area is shown in Figure 3. The uppermost bedrock beneath the city of Taconite consists of the Coleraine Formation, a Cretaceous sequence of conglomerate, hematite-cemented sandstone and blue-green shale (Jirsa and others, 2005). The thickness and distribution of this unit is poorly known. Morey (1999) indicates that it may be up to 100 feet thick in some areas of the western Mesabi Iron Range. However, it appears to be only 7 feet thick at the Taconite city wells, which are the only local data point. The Coleraine Formation is generally not considered to be an aquifer.

The Coleraine Formation lies unconformably on Paleoproterozoic rocks of the Animikie Group, which includes the Virginia Formation, the Biwabik Iron Formation, and the Pokegama Formation. These rocks, in turn, rest unconformably on Archean granitic rocks of the Giants Range Batholith. Rocks of the Animike Group dip southward around 4-15 degrees and have been diagenetically altered, but not significantly metamorphosed (Jirsa and others, 2005).

The Virginia Formation consists of interbedded carbonaceous shale, mudstone, siltstone, and fine-grained feldspathic greywacke (Jirsa and others, 2005). A cherty siderite layer occurs within the Virginia Formation in this area, which makes it difficult to distinguish from the underlying Biwabik Iron Formation. The Virginia Formation is generally not considered a productive aquifer. It is probably 50-100 feet thick at the city wells, although this is an estimate based on nearby boreholes. No Virginia Formation is described in the geologic record for Taconite Well 2 (495997), which is the only city well with a geologic record. However, this may simply be a misinterpretation stemming from the presence of the siderite-rich strata within the Virginia Formation in this area. The Virginia Formation thins out to the north, and the uppermost bedrock present within the Canisteo Mine Pit is the Biwabik Iron Formation (Jirsa and others, 2005).

The Biwabik Iron Formation is the dominant bedrock aquifer along the Mesabi Iron Range because of the combination of fracturing and solution-weathering that have occurred locally in its subcrop area. These same factors have accounted for the development of so-called "natural ores," portions of the iron formation where magnetite has been oxidized to hematite, thereby enriching the iron content. Natural ore mines dominated production on the Mesabi Range through the 1950s, after which most natural ore inventories were depleted and mining activity focused on the relatively unaltered iron formation or "taconite." Numerous natural ore mines existed in the Taconite area. After mining and dewatering ceased, these coalesced into the current Canisteo Mine Pit lake.

The complete thickness of the Biwabik Iron Formation in the Taconite area is probably on the order of 500 feet, although it thins out completely north of the Canisteo Mine Pit. It has been subdivided into four members, based largely on mineral content and texture (Figure 4). The Upper and Lower Cherty members consist mostly of thick-bedded, granular chert, iron silicates, magnetite and hematite; whereas the Upper and Lower Slaty members are predominantly thin-bedded iron silicates and carbonates, plus magnetite and hematite (Jirsa and others, 2005). A distinct carbonaceous marker horizon, known as the Intermediate Slate or "paint rock," separates the Lower Slaty and Lower Cherty members. The cherty members of the formation are probably the most hydraulically conductive because of their coarser texture. The city wells are probably open to the Upper Slaty and Upper Cherty members (Cotter and others, 1965).

The Biwabik Iron Formation is thought to have little primary porosity, and groundwater flow through this unit is thought to be controlled by faults, joints (both high-angle and bedding-plane), zones of solution-weathering, and man-made mining features such as drifts and shafts. Natural ore bodies were likely formed by interaction between the iron formation and groundwater (meteoric or hydrothermal). As a result, it is useful to analyze the nature of these ore bodies for possible insights into current groundwater flow patterns. Natural ore bodies in the Taconite area tend to be flat-lying features that follow specific stratigraphic horizons and are separated by layers of relatively unaltered slaty strata (Morey, 1999). These are often characterized by broad halos of oxidized iron formation (Bleifuss, 1964). Many such ore bodies have fissure or trough-like roots that follow fault or fold axes (Morey, 1999). In the Taconite area, major faults and folds trend northwest, with strikes ranging from approximately 315 to 335 degrees (Jirsa and others, 2005). Faults are normal, dip steeply, and their displacements are poorly known but probably minor. Joint sets mapped by Jirsa and others (2005) range in strike from 202 to 340 degrees, with an average value of 275 degrees. All mapped joints plunge deeply, with dips ranging from 70 to 90 degrees. To summarize, it is likely that groundwater flow through the Biwabik Iron Formation in the Taconite area is controlled by features such as 1) bedding plane contacts, which generally dip from 7 to 13 degrees in a southeasterly direction; 2) northwest-trending folds; and 3) steeply-dipping, high-angle faults and joints that strike approximately 275 to 335 degrees. Man-made mining features, such as shafts, drifts and adits, may also affect groundwater flow; however, it is not known if such features are present in the Taconite area.

The Pokegama Formation conformably underlies the Biwabik Iron Formation. It consists of quartzite, quartz-rich siltstone, shale, and localized basal conglomerate. This unit is probably around 80 feet thick in the Taconite area, based on the geologic mapping of Jirsa and others (2005). It is generally not considered an aquifer.

Groundwater Quantity and Quality: The Minnesota Department of Natural Resources permits high-capacity wells and documents their pumping volumes in the State Water Use Database (SWUDs). It is important to identify other high-capacity wells in the vicinity of the Taconite wells because they may affect the boundary of the capture zones in the WHPA. The only high-capacity well identified within two miles of the Taconite wells is the municipal well for Bovey. The Bovey city well is completed in a glacial sand and gravel aquifer and is unlikely to constitute a flow boundary to the Taconite wells.

Water quality information on the Taconite city wells was obtained from MDH records, as well as published data (Cotter and others, 1965). The parameters evaluated were chloride and sulfate, which can be useful indicators of general water quality. Elevated chloride is likely related to road de-icing salt, although fertilizer and wastewater are other possible sources. Elevated sulfate is generally related to naturally-occurring minerals, although wastewater is a possible source. Common mineral sources include gypsum, a soluble calcium sulfate mineral that occurs in minor amounts in some rocks, or the oxidation of sulfide-bearing minerals such as pyrite. Gypsum is not known to occur in the Biwabik Iron Formation or associated Precambrian rocks of the Taconite area, although it could be present in minor amounts in glacial drift or Cretaceous sediments. Pyrite is known to occur locally within both the Biwabik Iron Formation and the Virginia Formation and may be present in the Coleraine Formation, which tends to have a greater sulfur content than the Animikie Group rocks (Morey, 1999). It is possible that some of the waste rock stockpiles in the Taconite area contain pyrite, and result in localized occurrences of sulfate-rich groundwater. Evidence for this comes from water quality sampling conducted in 2004 on a ditch that drains into the north side of Trout Lake. The ditch originates at a wetland located at the toe of a waste rock stockpile along the south shore of the Canisteo Pit north of Coleraine. A sulfate value of 210 mg/l was determined for the ditch water.

The historic data from the Taconite city wells show that the chloride content of the water has remained relatively constant over time in the range of 1-4 mg/l, whereas the sulfate has increased somewhat (Figures 5 and 6). The earliest sulfate data for Well 1 (241489), dating to September 26, 1957, showed a value of 16 mg/l, compared with a value of 62 mg/l recorded on October 14, 2004. This change in sulfate levels may be attributed to changing groundwater flow patterns in the area related to rising Canisteo Mine Pit water levels. When the Canisteo Mine Pit complex was dewatered prior to the mid-1980s, the water level would have been 100-200 feet lower than currently observed (Figure 7). This would have created an hydraulic gradient much greater than currently exists in the area. As a result, the capture areas for the city wells likely extended much further to the south than is currently indicated.

Data on the chloride, sulfate, and oxygen and hydrogen stable isotope content of Canisteo Mine Pit lake water was obtained from samples collected at several locations in the summer and fall of 2004. These results were compared with data obtained from the Taconite city wells to estimate whether water from the Canisteo Mine Pit lake was being captured by the city wells. The chloride and sulfate data show that similar values are seen at both the city wells and the pit lake. However, the stable isotope data show that little, if any, pit lake water was being captured by the city wells as of the latest sampling episode, which was October 14, 2004 (Figure 8). The samples from the Canisteo Mine Pit lake showed values that were consistently far removed from the meteoric water line, suggesting that the lake has undergone a high degree of evaporation. However, each of the city well samples plot within the limits of analytical uncertainty of the global meteoric water line, with the exception of a single sample from Well 1 (241489) collected on June 2, 2004. That value may represent a questionable result, given that it plots off both the meteoric water line and the evaporation trend defined by data from the city wells and the Canisteo Mine Pit lake. In addition, a subsequent sample collected on October 14, 2004, plotted within the limits of uncertainty of the meteoric water line. In light of the stable isotope data, the similarities noted between the chloride and sulfate values for the city wells and the Canisteo Mine Pit lake probably reflect that the recharge areas for both have comparable water quality.

In addition to the chemical and isotopic data noted above, the Taconite city wells have been sampled for tritium to determine the residence time or "age" of the water. Well 1 (241489) was sampled on September 4, 1991, and February 9, 2004, with results of 20.1 and 17.2 tritium units (TU). Well 2 was also sampled on February 9, 2004, and that result showed 19.7 TU. These results demonstrate that the Biwabik Iron Formation aquifer at this location is dominated by relatively young water that entered the ground since 1954.

Hydrogeological Setting

In the geographic area that includes the WHPA, the aquifer from which the city well pumps has the following characteristics:

- It is composed of chert and iron minerals and is approximately 500 feet thick;
- It exhibits a porosity that is estimated to range from 1-10 %;
- It exhibits a base elevation of approximately 500 feet above sea level at the city wells and rises to the north at approximately 7 to 13 degrees;
- It exhibits a stratigraphic top elevation of approximately 1,000 feet above sea level at the city wells and rises to the north at approximately 7 to 13 degrees;
- It is bounded stratigraphically by relatively impermeable bedrock units in addition to a significant thickness of till.

The aquifer generally exhibits confined hydraulic conditions. This was determined by comparing the static water level measurements from Well 2 (495997) with the stratigraphic top of the Biwabik Iron Formation aquifer (Figure 4). The static water level occurs in the till that overlies the aquifer. However, the aquifer is unconfined where it is intersected by the Canisteo Mine Pit (Figures 3 and 4).

The Minnesota Department of Natural Resources (DNR) has developed a procedure for determining geologic sensitivity at well sites (DNR, 1991). The Taconite city wells exhibit a geologic sensitivity rating of moderate using the DNR criteria.

The groundwater flow field for the Biwabik Iron Formation is not known with certainty because of the lack of wells with water level data in this area. In addition, the potentiometric surface has probably been strongly altered by mine dewatering. Nothing is known of pre-mining groundwater conditions, but it is certain that mining activities have significantly altered groundwater flow patterns in the area. It is likely that under pre-mining groundwater conditions, the direction of groundwater flow in both the glacial deposits and the Biwabik Iron Formation was generally to the south or southeast, down-dip from the Giants Range.

Current data suggest that the mine pit complexes represent the low points on the potentiometric surface, and that the dominant groundwater flow direction is northwesterly in the Taconite area (Figure 9). This estimated was based on 1) static water level measurements obtained from Taconite Well 2 (495997) on December 15, 2006, and Taconite Well 1 (241489) taken on November 17, 2004; 2) water level information from the DNR on the Canisteo Mine Pit lake and Holman Lake (DNR Lakefinder web site and Bob Liebfried, personal communication, 2006); 3) information contained in the Environmental Supplement to the permit application for the Mesaba Energy Project (2006) on current water levels in the Arcturus and Hill Annex mines; and 4) potentiometric contours produced from the groundwater flow model of Jones (2002). Groundwater movement upgradient of the Taconite city wells is presumed to be in a northwesterly direction (approximately 330 degrees). The horizontal gradient is unknown upgradient of the city wells because no data points exist. However, if it is similar to that observed between the city wells and the Canisteo Mine Pit lake, then it is approximately 0.005. The presence of a 77-foot deep monitoring well (Unique No. 629812) outside the Taconite well house allows for an estimation of the vertical gradient between the glacial drift and the Biwabik Iron Formation at this location. As of 2006, the vertical gradient is steeply downward, with a value of 0.126 (Figure 7). This implies that the aquifer is recharged in part by vertical leakage through the glacial drift and Virginia Formation. This interpretation is consistent with the tritium data for the Taconite city wells showing that young water is dominant.

Criteria Used to Delineate the Wellhead Protection Area

The criteria for delineating the WHPA, as required in Minnesota Rules 4720.5510, were addressed as follows.

Time of Travel - A time of travel criterion is difficult to apply to an aquifer such as the Biwabik Iron Formation, where flow occurs through well-developed secondary porosity features. As a result, a cylinder was calculated using a 10-year pumping volume to account for the ambiguity of flow directions caused by secondary porosity. Also, an emergency response area (ERA) was defined, as specified under Minnesota Rules 4720.5250, using the one-year pumping volume.

Daily Volume of Water Pumped – Information provided by the city of Taconite was used to determine the maximum discharge from their wells. The results are presented in the following table. The daily volume of discharge used as an input parameter in the model was calculated by dividing the greatest annual pumping volume by 365 days.

Table 3
Annual Volume of Water Discharged From Taconite Water Supply Wells

Well No.	Unique No.	2001	2002	2003	2004	2005	Future Pumping
1	228837	5,700,000	6,500,000	6,600,000	7,961,000	**8,465,000**	No Increase Expected
2	495997	6,900,000	6,700,000	6,700,000	7,299,000	**8,754,000**	No Increase Expected

(Expressed as gallons. Bolding indicates greatest annual pumping volume.)

The values shown in Table 3 are the total number of gallons pumped annually by the Taconite city wells and reported to the Minnesota Department of Natural Resources under Groundwater Appropriations Permit No. 792206. The city of Taconite indicates that it intends to pump approximately the same amounts of water during the next five years. As a result, the maximum amount of annual pumping, shown in bold above, was used to express the daily volume of water pumped from the city wells.

The maximum annual volume pumped by Taconite Wells 1 and 2 (241489 and 495997) over the 2001-2005 time period was incorporated as a daily volume in the calculations used to designate the capture zones for the wells. For delineation purposes, the following pumping rates were applied to the wells. The rates selected are consistent with WHP rule requirements because the maximum volume is used.

Table 4
Pumping Rates Used for WHPA Delineation

Well Number	Equivalent Annual Volume (gallons)	Input Value (cubic meter/day)
1	8,465,000	88
2	8,754,000	91

Groundwater Flow Field - The groundwater flow field was determined by compiling static water level elevations from 1) wells that are completed in the same aquifer used by the city of Taconite, and 2) fully-penetrating surface water features such as the Canisteo Mine Pit lake, as described above and displayed in Figure 9. The ambient flow field in the aquifer upgradient of the city wells is oriented in a northwesterly direction (approximately 330 degrees) with a horizontal gradient of approximately 0.005.

Aquifer Transmissivity - Because of the fractured nature of the Biwabik Iron Formation aquifer, transmissivity was not used to delineate the WHPA, consistent with the "Guidance for Delineating Wellhead Protection Areas in Fractured and Solution-Weathered Bedrock in Minnesota" (MDH, 2005).

Flow Boundaries - The following conditions define the extent to which flow boundaries must be considered:

> Geologic boundaries that must be considered include 1) the stratigraphic top and bottom of the Biwabik Iron Formation, and 2) the orientation of dominant geologic structures such as folds, faults and joints. Hydrologic boundaries that must be considered include surface water features that at least partially penetrate the aquifer, including the Canisteo Mine Pit lake. If present, other high-capacity wells that pump from the Biwabik Iron Formation would also need to be accounted for in the delineation. However, no such wells could be found within two miles of the Taconite city wells.

Method Used to Delineate the Wellhead Protection Area - In aquifers influenced by flow through secondary porosity, groundwater may move a much greater distance to supply a pumping well than in porous media aquifers. In addition, flow directions are considerably more variable in aquifer settings influenced by fractures or conduit flow. Therefore, numerical and analytical methods that traditionally are used to designate capture zones for wells completed in porous media aquifers may not apply to fractured and solution-weathered bedrock aquifers. To account for this, MDH has developed the document entitled, "Guidance for Delineating Wellhead Protection Areas in Fractured and Solution-Weathered Bedrock in Minnesota" (MDH, 2005).

According to the guidance, a fracture flow analysis is required when the aquifer exhibits flow through secondary porosity features, as is presumed for the Biwabik Iron Formation. Of the various delineation methods specified in the guidance document, Delineation Technique 2 is most appropriate. This technique is specific to fractured or solution-weathered aquifers that 1) are hydraulically confined, 2) have a horizontal hydraulic gradient greater than 0.001, and 3) possess a well discharge to discharge vector ratio of less than 3,000 (MDH, 2005).

The formula and values used for calculating the ratio of the well discharge to the discharge vector are presented below:

$$Q/Q_s = \frac{(Q\ \ in\ \ gpm)(\frac{1 ft^3}{7.48\, gal})(\frac{1440\,\text{min}}{1\, day})(\frac{0.0283 m^3}{1 ft^3})}{(thickness\ in\ ft)(0.3048\, m/ft)(hydraulic\ conductivity\ in\ m/d)(hydraulic\ gradient)}$$

Q = Well Discharge (L^3/T)

Q_s = Discharge Vector (L^2/T) = (H) (K) i

Where: H = aquifer thickness (L)

K = hydraulic conductivity (L/T)

i = hydraulic gradient

For the Taconite city wells: 1) the well discharge was determined from the annual water use figures; 2) the aquifer thickness was determined to be 94 feet, which represents the maximum open interval of the two city wells; 3) the hydraulic conductivity was estimated to be 4.7 ft/day, based on specific capacity data for Well 2 (495997) determined using the method described in Appendix III; and 4) the hydraulic gradient was estimated to be 0.005. The resulting well discharge to discharge vector ratio is 890.

Delineation Technique 2 uses a calculated fixed radius to represent the volume of aquifer material needed to supply water to the city wells over a 10-year time period. The calculated fixed radius was then modified to account for 1) upgradient groundwater flow, 2) ambiguity of the groundwater flow direction, and 3) the effects of the orientations of secondary porosity features, such as fractures and faults. Details of this approach are presented below.

The calculated fixed radius (CFR) is a simple volumetric calculation for a cylinder that would supply the discharge amount for the well, based on 1) the highest pumping rate in the last five years, 2) the thickness of the open hole length of the well, and 3) the effective porosity of the aquifer.

$$R = \sqrt{\frac{Q}{nL\pi}}$$

where: R = radius of the capture area

Q = well discharge = (well pumping rate)(pumping time period)

n = effective porosity

L = open hole length of the well

$\pi = 3.14159$

The CFR calculation was based on the following:

- 10 years of pumping.
- Q = 172,190,000 gallons, which is the annual pumping rate multiplied by the number of years of pumping. Table 3 lists the maximum annual pumping rate for the city wells. This value represents the combined pumping of both city wells, and was applied to Well 2 (495997) to represent the cumulative discharge from both city wells. This approach is considered appropriate given that the wells are located within approximately 40 feet of each other.
- n = 0.01. This value represents the low end of the estimated range shown in the MDH guidance document (2005) for dolomite and limestone. No specific category exists for iron formation, and limestone is considered to be a reasonable equivalent given that both are marine chemical sediments. The low end of the estimated porosity range was used because it was not possible to determine specific productive horizons within the open hole intervals of the city wells. If such determinations can be made at a later date, then future delineations could be based on a larger porosity value, which should result in a smaller CFR (MDH, 2005).
- L = 94 feet. This is the open hole interval for Well 2 (495997). Well 1 (241489) has an open hole interval of 91 feet. Using this value rather than the entire thickness of the Biwabik Iron Formation (approximately 500 feet) results in a more conservative well capture zone. However, it is likely that certain stratigraphic horizons within the Biwabik Iron Formation are more hydraulically active than others, and the actual productive aquifer thickness may be less than the open hole interval used in this calculation.

Using the values noted above, the CFR for the Taconite city wells is 2,792 feet (Figure 10). In order to account for upgradient groundwater flow, the CFR noted above was projected in the dominant upgradient flow direction for an additional 10-year pumping volume. This projection was then adjusted plus and minus 10 degrees from the dominant flow direction to account for uncertainty in the groundwater flow field (Figure 10). Finally, the CFR was projected an additional 10-year pumping volume upgradient along the dominant trend of linear bedrock structural features, such as faults and fold axes (Figure 10). The resulting WHPA for the city of Taconite is a composite of these delineation methods.

Results of Model Calibration and Sensitivity Analysis - The fracture flow delineation procedure cannot be calibrated because it is a simple calculation of an aquifer volume based on well discharge, open borehole thickness, and effective porosity.

Model Sensitivity - Model sensitivity refers to the amount of change in model results caused by the variation of a particular input parameter. Because of the fractured nature of the Biwabik Iron Formation aquifer, a porous-media groundwater flow model was not used to delineate the WHPA. As a result, no model sensitivity analysis was performed. However, an effort was made to assess the sensitivity of the WHPA to the input parameters used in the CFR calculation and extrapolation.

The CFR calculation is sensitive to the pumping rate of the well, in addition to aquifer thickness and porosity. The well pumping rate used in the CFR calculation is prescribed in the state's wellhead protection rule (Minnesota Rules 4720.5510, subpart 4) and is a conservative value because it is based on the highest recorded value for the wells. The use of any smaller value in the CFR calculation would result in a reduced CFR and WHPA.

Aquifer thickness and porosity are indirectly proportional to the resulting CFR; larger values result in smaller CFR's and vice-versa. The aquifer thickness used in the CFR calculation is based on the open hole interval of 94 feet. This value is much smaller than the complete thickness of the Biwabik Iron Formation, which is on the order of 500 feet. As a result, it is a conservative value. However, it is likely that certain stratigraphic horizons or fracture zones present within the open hole interval are responsible for most of the groundwater flow to the city wells. Uncertainty regarding this parameter resulted in the use of a very low porosity value in the CFR calculation (0.01), which counteracts any exaggeration of true aquifer thickness and results in a conservative capture zone. For comparison, a WHPA based on a porosity value of 0.05 is shown in Figure 11.

The extrapolation of the CFR is sensitive to the 1) ambient groundwater flow direction, and 2) orientation of dominant geologic structural features. Uncertainty in the groundwater flow field was accounted for by creating a composite of capture zones from angles of flow that are 10 degrees greater and 10 degrees lesser than the representative angle of ambient flow (Minnesota Rule 4720.5510, subpart 5, B(2). The orientation of dominant geologic structural features was based on the geologic mapping of Jirsa and others (2005). The variation in the strike of dominant structural features was accounted for by utilizing the range of observed values.

Uncertainty Analysis - As noted above, the WHPA for the city of Taconite is sensitive to a variety of input parameters. The least well known of these parameters are aquifer thickness, porosity, and groundwater flow field. The following section describes steps that could be taken to provide a greater degree of certainty in the calculated capture zone.

Recommendations for Future Data Collection

1) Enhancing the Understanding of Local Hydrogeologic Conditions.

Aquifer Thickness and Porosity -

- It is possible to accurately determine the location and hydraulic properties of distinct flow horizons in a well using sophisticated logging equipment, such as flow meters and water quality probes. The Minnesota Geological Survey and the MDH currently possess such equipment and would likely consent to its use at the Taconite city wells under appropriate conditions. The minimum conditions required for successful deployment of this equipment include 1) the well(s) must be accessible and open (no pumps or related equipment in the well), and 2) adequate notice must be provided so the equipment can be mobilized. If the city of Taconite plans to conduct maintenance or repair on either of their wells that would involve short-term removal of the well pump(s), they should contact the MDH to arrange for this type of borehole investigation. The results should allow for a more accurate determination of the thickness of the water-producing horizons penetrated by the wells. With that information in hand, the CFR and resulting WHPA could be refined using the appropriate aquifer thickness and porosity.

Groundwater Flow Field -

- Every five years, the city of Taconite should work with the MDH so that the locations of new wells constructed within one mile of the city's well field can be verified and accurate elevations obtained. This information may help address uncertainties related to the distribution of hydraulic head in the Biwabik Iron Formation aquifer.
- The city of Taconite should work with the MDH so that the static water level at the city wells can be determined on an annual basis. This information can be used in conjunction with water level data from the Canisteo Mine Pit lake and other mine pits and wells to verify the local horizontal hydraulic gradient. This is especially important with regard to the Canisteo Mine Pit lake because 1) it is the closest hydrologic boundary to the Taconite city wells, and 2) its water level is subject to considerable change depending on various water level control and development scenarios that have been recently proposed. If the horizontal hydraulic gradient were to change, such that it became 0.001 or less, then a different delineation technique would be indicated for the city's WHPA.
- *Hydraulic Conductivity* - Although this parameter is not used directly in the calculation of the city of Taconite's WHPA, it does factor into determining the appropriate delineation technique because of its impact on the well discharge to discharge vector calculation (MDH, 2005). For this delineation, hydraulic conductivity was estimated using specific capacity data from Well 2 (495997). This method of estimating specific capacity is less accurate than an aquifer test conducted for determining aquifer transmissivity. It may be beneficial for the city of Taconite to conduct an aquifer test in the future so that the hydraulic conductivity of the Biwabik Iron Formation aquifer can be more accurately determined. The MDH can assist the city with planning and conducting such a test.

2) Surface Water/Groundwater Exchange.

Chemical and Isotopic Data -

Existing isotopic data suggest that the Taconite city wells were not capturing an identifiable component of Canisteo Mine Pit lake water as of October, 2004. It is possible that this relationship could change through time, either because of increases in water use by the city, or an increase in water level elevation within the mine pit lake. In order to track whether such changes may be occurring and verify the accuracy of the currently delineated WHPA, the MDH recommends that one of the city wells be sampled for the stable isotopes of water, chloride, and sulfate on an annual basis. The city will be responsible for most of the sampling, but the MDH will pay for the analyses using funding that it has dedicated for this work. There would be no cost to the city for the analyses and MDH staff time. If it became apparent that the city wells were capturing a significant component of Canisteo Mine Pit lake water, then that feature and its surface watershed area would need to be added to the WHPA for the city of Taconite.

3) Water Use Considerations.

Revisions to the WHPA -

The following water use factors should be monitored to determine if a revision of the WHPA or DWSMA is required: 1) the installation of any new high-capacity wells within 1.5 miles of the city well field, and 2) increased discharge from the city wells over the values used in this report.

Delineation of the Drinking Water Supply Management Area

Method Used to Designate the Drinking Water Supply Management Area - The Drinking Water Supply Management Area (DWSMA) was determined by overlaying the WHPA on a map of area roads, railroads, and public land survey boundaries and using a geographic information system to select the closest such feature. This area was then reviewed and modified by staff from the city of Taconite and the MDH.

Assessment of Well Vulnerability

This part documents the vulnerability of the wells used by the public water supplier and is required under Minnesota Rules 4720.5210. The protocol for determining well vulnerability is defined in the MDH document entitled Methodology for Phasing Wells into Minnesota's Wellhead Protection Program (1993), which was approved by the U.S. Environmental Protection Agency as part of its review of Minnesota's wellhead protection program description. The MDH uses the protocol to maintain a database defining the potential vulnerability of community and noncommunity public water supply wells. A score is calculated for each well using 1) construction criteria defined in the State Well Code, 2) geologic sensitivity, and 3) the results of water quality monitoring conducted by the MDH. A numeric score is assigned to each well based on the results of the three areas of evaluation. A cutoff score is used to define wells that are most likely to be vulnerable based on their construction, geologic setting, and sampling history. The printouts of the vulnerability ratings for each well are presented in Appendix I.

The results of the well vulnerability assessments suggest that the wells used by the city of Taconite are potentially vulnerable to contamination. This conclusion is based primarily on the fact that water samples collected from the city wells on February 9, 2004, contained tritium at 17.1 and 19.7 tritium units, indicating the predominance of young (post-1954) water in the samples. An additional factor is that Well 1 (241489) does not meet current standards for construction.

Vulnerability Assessment for the Drinking Water Supply Management Area

The aquifer used by the Taconite city wells was evaluated for its vulnerability to contamination throughout the extent of the DWSMA on the basis of 1) geologic and soils maps, 2) geologic logs from wells in the area, and 3) the chemical and isotopic data noted above.

The Itasca County Soil Survey includes an assessment of the geologic sensitivity at the water table based on the criteria of the DNR (1991). The geologic sensitivity ratings within the Taconite DWSMA range from very high to low. These ratings correlate strongly with the surficial geologic mapping of Jennings and Reynolds (2005). Geologic sensitivity ratings of very high or high correspond to the occurrence of relatively coarse sediments associated with glacial outwash or ice contact deposits. These are most prevalent around Trout and Holman Lakes, which have been interpreted to be the remnants of sub-glacial drainage features (Jennings and Reynolds, 2005). Very high geologic sensitivity ratings are also assigned within the Canisteo Mine Pit lake, where till that originally overlay the Biwabik Iron Formation aquifer has been removed by mining. Geologic sensitivity ratings of moderate and low are assigned where the soil has a relatively high clay or loam content, suggesting that till was the parent material. These areas are strongly correlated with those areas mapped as Koochiching lobe till by Jennings and Reynolds (2005).

The geologic sensitivity ratings described above were compared with that from Taconite city Well 2 (495997), which is the only well with a complete stratigraphic record that is 1) completed in the Biwabik Iron Formation, and 2) located within or near the city's DWSMA. The geologic sensitivity rating for that well is moderate, which is consistent with the rating suggested by surficial geologic mapping (Figure 12). Geologic protection at the city well field consists of clay-rich till and the Virginia Formation. Although the Virginia Formation thins to a feather-edge approximately 1,300 feet north of the Taconite city wells, based on the mapping of Jirsa and others (2005), till cover continues to the edge of the Canisteo Mine Pit. At that point, the Biwabik Iron Formation is exposed.

The chemical and isotopic data for the Taconite city wells suggest that the Biwabik Iron Formation is characterized by the presence of young water. As a result, the overlying geologic protection provided by the Virginia Formation and till cover is considered to be leaky. This is consistent with a moderate vulnerability rating. Those areas determined to exhibit a geologic sensitivity rating of low, based on surficial geologic mapping, were increased to a vulnerability rating of moderate to reflect the leaky nature of the till. Finally, mapped areas smaller than approximately 10-acres in size were incorporated within the surrounding mapped area so as to avoid small slivers of land that would be difficult to identify and manage.

In summary, the vulnerability of the Biwabik Iron Formation aquifer is moderate throughout the city of Taconite DWSMA. Within areas rated as moderate, the time required for water moving vertically from the land surface to reach the aquifer is probably on the order of several years to decades (DNR, 1991).

Selected References

Bleifuss, R.L. (1964), *Mineralogy of oxidized taconites of the western Mesabi and its influence on metallurgical processes,* Society of Mining Engineers Transactions, v. 229, 236-244 p.

Cotter, R.D., Young, H.L., Petri, L.R., and Prior, C.H. (1965), *Water resources in the vicinity of municipalities on the western Mesabi Iron Range, northeastern Minnesota*, U.S. Geological Survey Water Supply Paper 1759-B.

Geologic Sensitivity Project Workgroup (1991), *Criteria and guidelines for assessing geologic sensitivity of ground water resources in Minnesota,* Minnesota Department of Natural Resources, Division of Waters, St. Paul, Minn., 122 p.

Excelsior Energy (2006), *Environmental supplement to the joint application to the Minnesota public utilities commission for the Mesaba energy project,* Unpublished.

Jones, P.M. (2002), *Characterization of ground-water flow between the Canisteo Mine Pit and surrounding aquifers, Mesabi Iron Range, Minnesota*, U.S. Geological Survey Water Resources Investigations Report 02-4198.

Jennings, C.E., and Reynolds, W.K. (2005), *Surficial geology of the Mesabi Iron Range, Minnesota,* Miscellaneous Map Series, M-164, Minnesota Geological Survey, St. Paul, Minn., 1 sheet, scale 1:100,000.

Jirsa, M.A., Chandler, V.W., and Lively, R.S. (2005), *Bedrock geology of the Mesabi Iron Range, Minnesota,* Miscellaneous Map Series, M-163, Minnesota Geological Survey, St. Paul, Minn., 1 sheet, scale 1:100,000.

Minnesota Department of Health (1996), *Methodology for phasing wells into Minnesota's wellhead protection program,* Minnesota Department of Health, St. Paul, Minn., 18 p.

Minnesota Department of Health (2005), *Guidance for delineating wellhead protection areas in fractured and solution-weathered bedrock in Minnesota,* Minnesota Department of Health, St. Paul, Minn., 80 p.

Morey, G.B. (1999), *High-grade iron ore deposits of the Mesabi Range, Minnesota – product of a continental-scale proterozoic ground-water flowsSystem*, Economic Geology, Vol. 94, 133-142 p.

Nyberg, P.R. (1987), *Soil survey of Itasca County, Minnesota,* Soil Survey, U.S. Department of Agriculture, Soil Conservation Service, Fort Worth, Tex., 197 p., 65 sheets, scale 1:24,000.

Oakes, E.L. (1970), *Geology and ground-water resources of the Grand Rapids area, north-central Minnesota*, Hydrologic Investigations Atlas HA-322.

Winter, T.C. (1971), *Sequence of glaciation in the Mesabi-Vermillion Iron Range area, northeastern Minnesota*, U.S. Geological Survey Professional Paper 750-C, p. C82-C88.

Winter, T.C. (1973a), *Hydrogeology of glacial drift, Mesabi Iron Range, northeastern Minnesota*, U.S. Geological Survey Water Supply Paper 2029-A, 23 p.

Appendix I

Municipal Well Information

Table 1
Municipal Water Supply Well Information
Taconite, Minnesota

Local Well Name	Unique Number	Use/ Status[1]	Casing Diameter (inches)	Casing Depth (feet)	Well Depth (feet)	Date Constructed/ Reconstructed	Well Vulnerability	Aquifer
1	241489	P	18	293	384	1936	Vulnerable	PEBI
2	495997	P	12	300	394	1991	Vulnerable	PEBI

Note: 1. Primary (P) or Emergency backup (E) well

625 Robert St. N. St. Paul MN 55155
P.O. Box 64975 St. Paul MN 55164 - 0975

MINNESOTA DEPARTMENT OF HEALTH
SECTION OF DRINKING WATER PROTECTION
SWP Vulnerability Rating

PWSID: 1310028
SYSTEM NAME: Taconite
WELL NAME: Well #1

TIER: 3
WHP RANK:
UNIQUE WELL #: 00241489

COUNTY: Itasca   TOWNSHIP NUMBER: 56   RANGE: 24 W   SECTION: 27   QUARTERS: BBCB

CRITERIA		DESCRIPTION	POINTS
Aquifer Name(s)	:	Biwabik Iron-Formation	
DNR Geologic Sensitivity Rating	:	Medium	25
L Score	:	0	
Geologic Data From	:	Data Inferred From Nearby Wells	
Year Constructed	:	1936	
Construction Method	:	Cable Tool/Bored	0
Casing Depth	:	293	5
Well Depth	:	384	
Casing grouted into borehole?		Unknown	0
Cement grout between casings?		Unknown	5
All casings extend to land surface?		Yes	0
Gravel - packed casings?		No	0
Wood or masonry casing?		No	0
Holes or cracks in casing?		Unknown	0
Isolation distance violations?			0
Pumping Rate	:	250	5
Pathogen Detected?			0
Surface Water Characteristics?			0
Maximum nitrate detected	:	.1 09/04/1991	0
Maximum tritium detected	:	20.1 09/04/1991	VULNERABLE
Non-THMS VOCs detected?			0
Pesticides detected?			0
Carbon 14 age	:	Unknown	0
Wellhead Protection Score	:		40
Wellhead Protection Vulnerability Rating	:		VULNERABLE
Vulnerability Overridden	:		

COMMENTS
GEOLOGY INFERRED FROM WELL 495997

MINNESOTA DEPARTMENT OF HEALTH
SECTION OF DRINKING WATER PROTECTION
SWP Vulnerability Rating

625 Robert St. N. St. Paul MN 55155
P.O. Box 64975 St. Paul MN 55164 - 0975

PWSID: 1310028
SYSTEM NAME: Taconite
WELL NAME: Well #2

TIER: 3
WHP RANK:
UNIQUE WELL #: 00495997

COUNTY: Itasca | TOWNSHIP NUMBER: 56 | RANGE: 24 W | SECTION: 27 | QUARTERS: BBCB

CRITERIA		DESCRIPTION	POINTS
Aquifer Name(s)	:	Biwabik Iron-Formation	
DNR Geologic Sensitivity Rating	:	Medium	25
L Score	:	0	
Geologic Data From	:	Well Record	
Year Constructed	:	1991	
Construction Method	:	Rotary/Drilled	0
Casing Depth	:	300	5
Well Depth	:	394	
Casing grouted into borehole?		Yes	0
Cement grout between casings?		Not applicable	0
All casings extend to land surface?		Yes	0
Gravel - packed casings?		No	0
Wood or masonry casing?		No	0
Holes or cracks in casing?		Unknown	0
Isolation distance violations?			0
Pumping Rate	:	225	5
Pathogen Detected?			0
Surface Water Characteristics?			0
Maximum nitrate detected	:	Unknown	0
Maximum tritium detected	:	19.7 02/09/2004	VULNERABLE
Non-THMS VOCs detected?			0
Pesticides detected?			0
Carbon 14 age	:	Unknown	0
Wellhead Protection Score	:		35
Wellhead Protection Vulnerability Rating	:		VULNERABLE
Vulnerability Overridden	:		Jim Walsh

COMMENTS

Appendix II

Figures Used In This Report

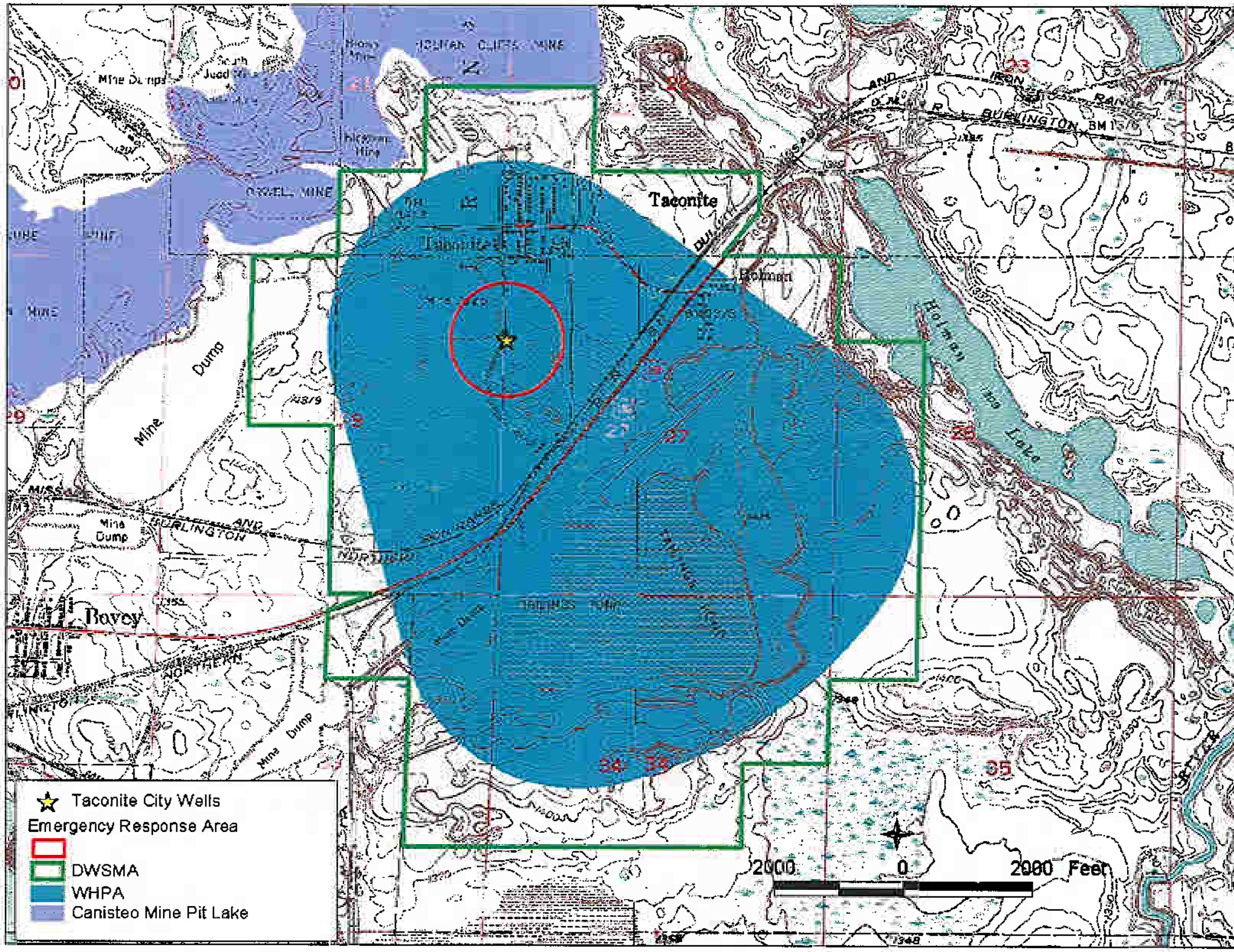

Figure 1. Wellhead protection area (WHPA), drinking water supply management area (DWSMA) and emergency response area (ERA) for the city of Taconite.

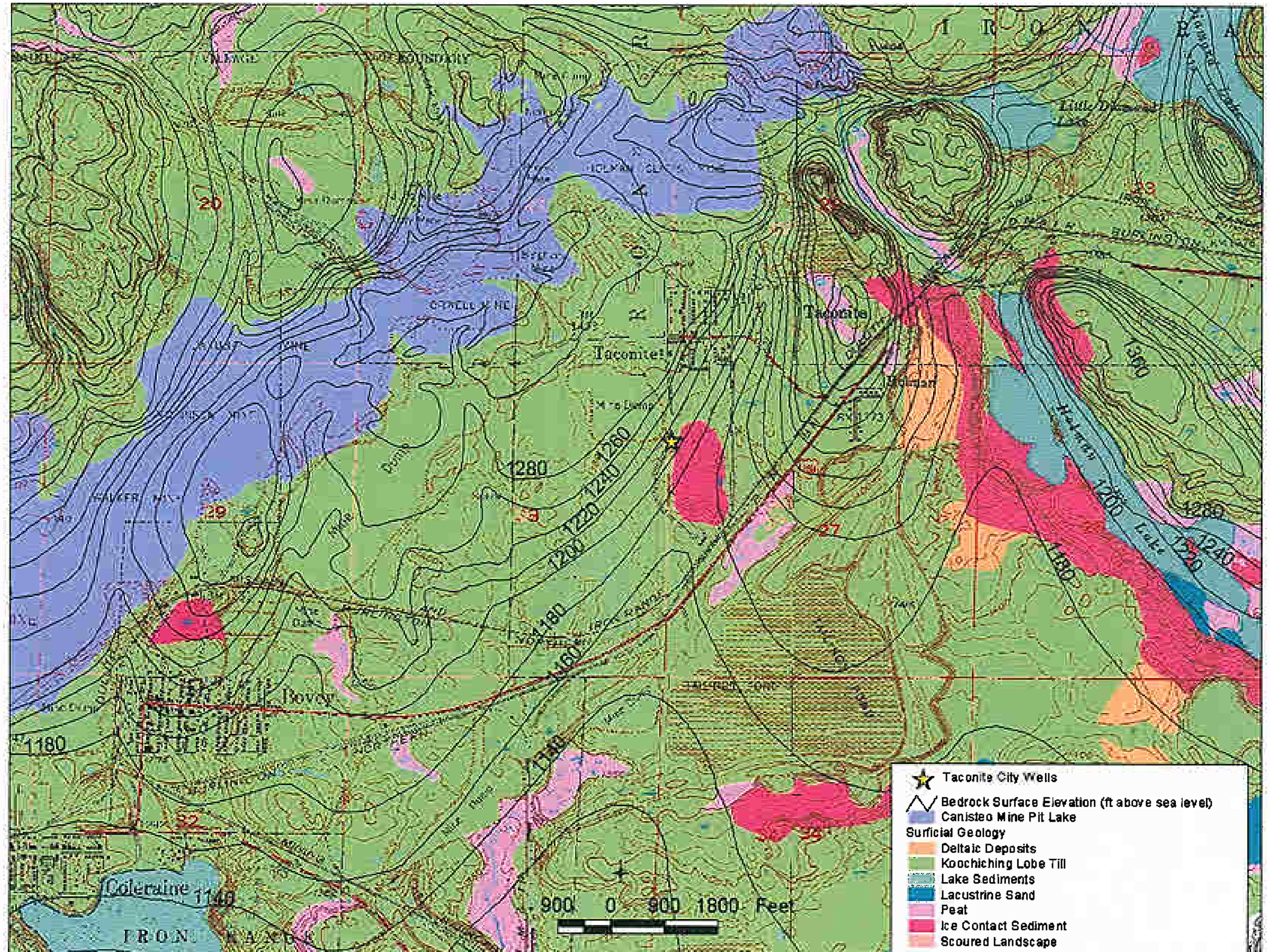

Figure 2. Surficial geology of the Taconite area (Jennings and Reynolds, 2005).

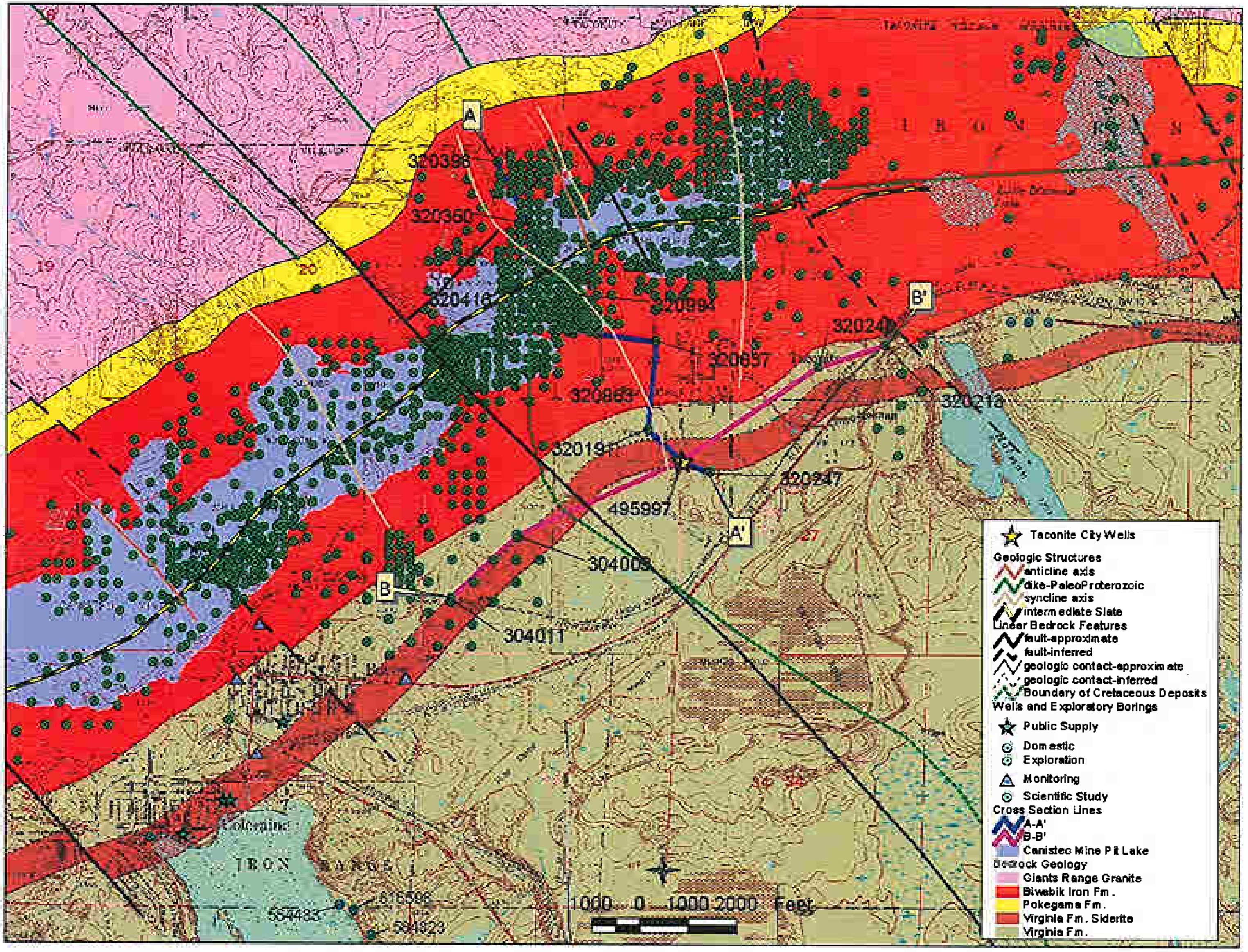

Figure 3. Bedrock geology of the Taconite area (Jirsa and others, 2005).

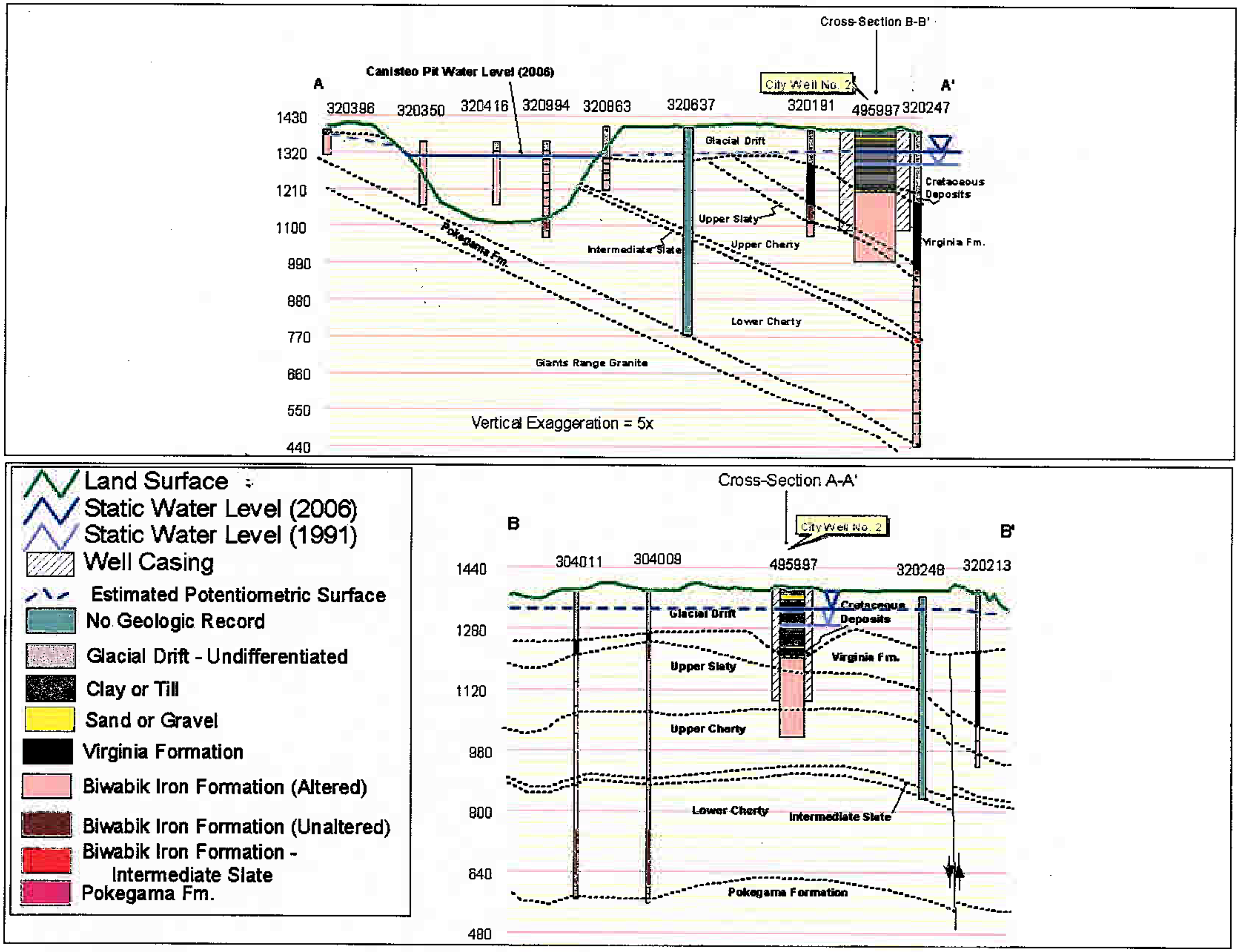

Figure 4. Geologic cross-sections through the Taconite area.

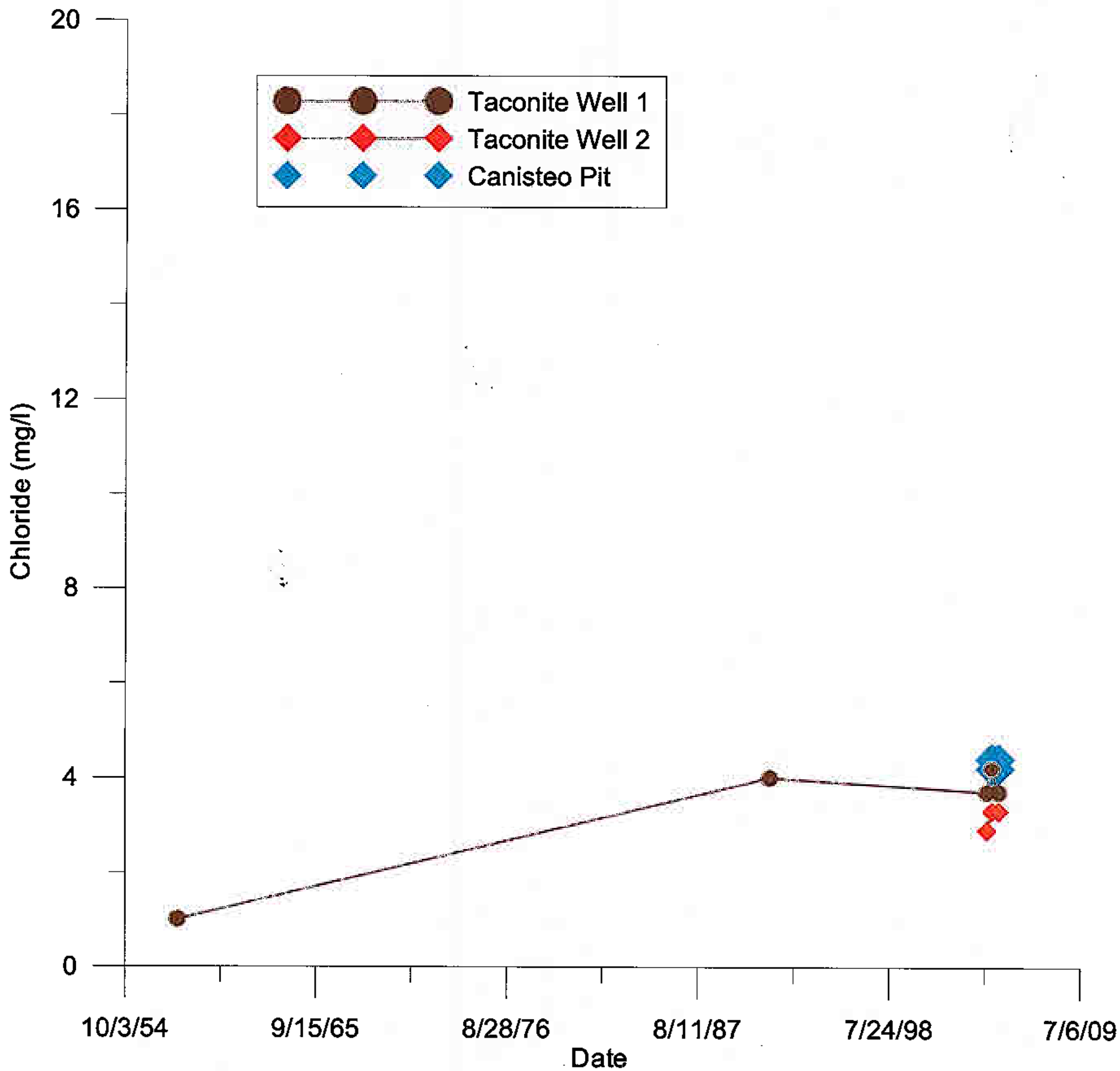

Figure 5. Chloride data through time.

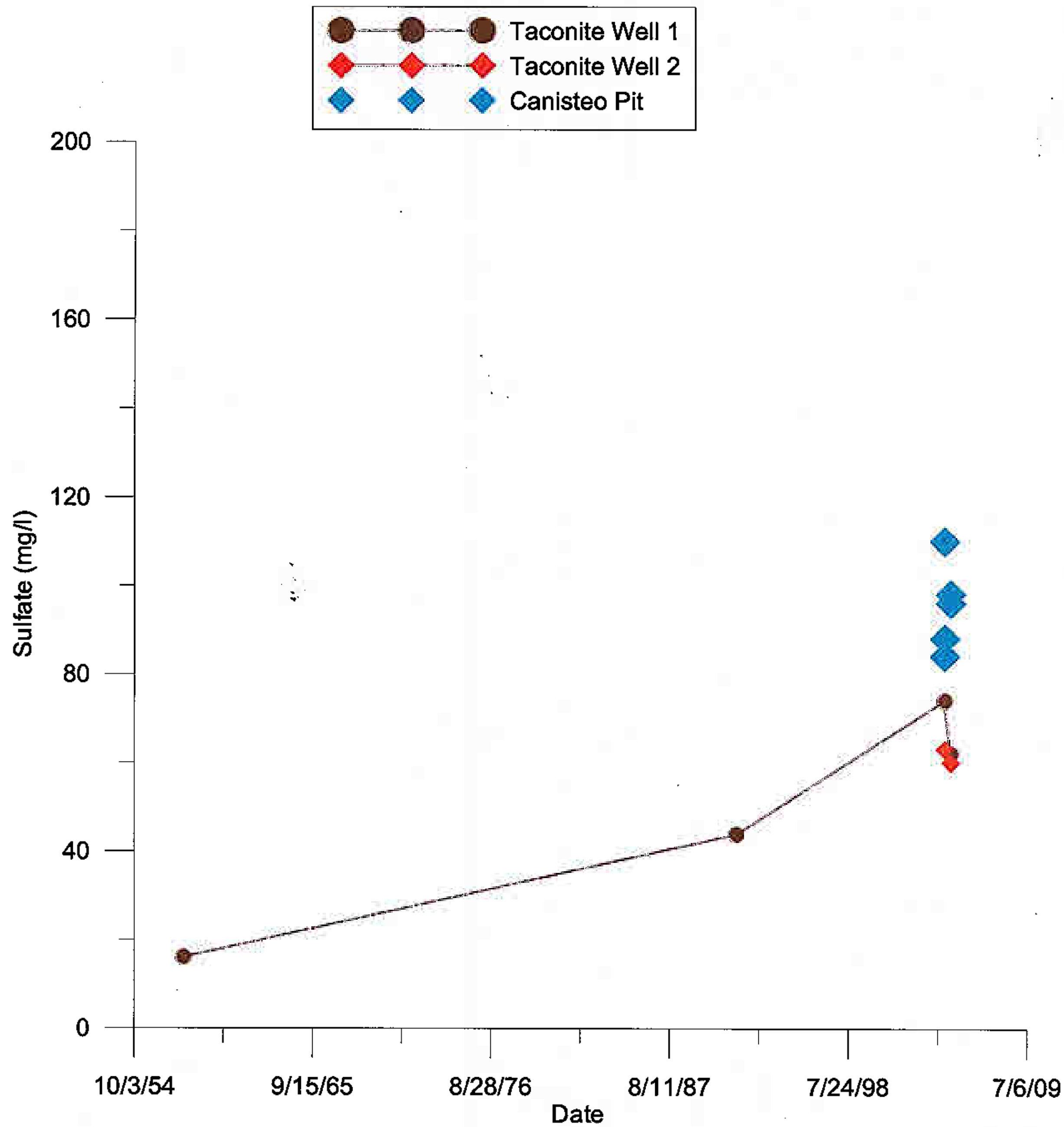

Figure 6. Sulfate data through time.

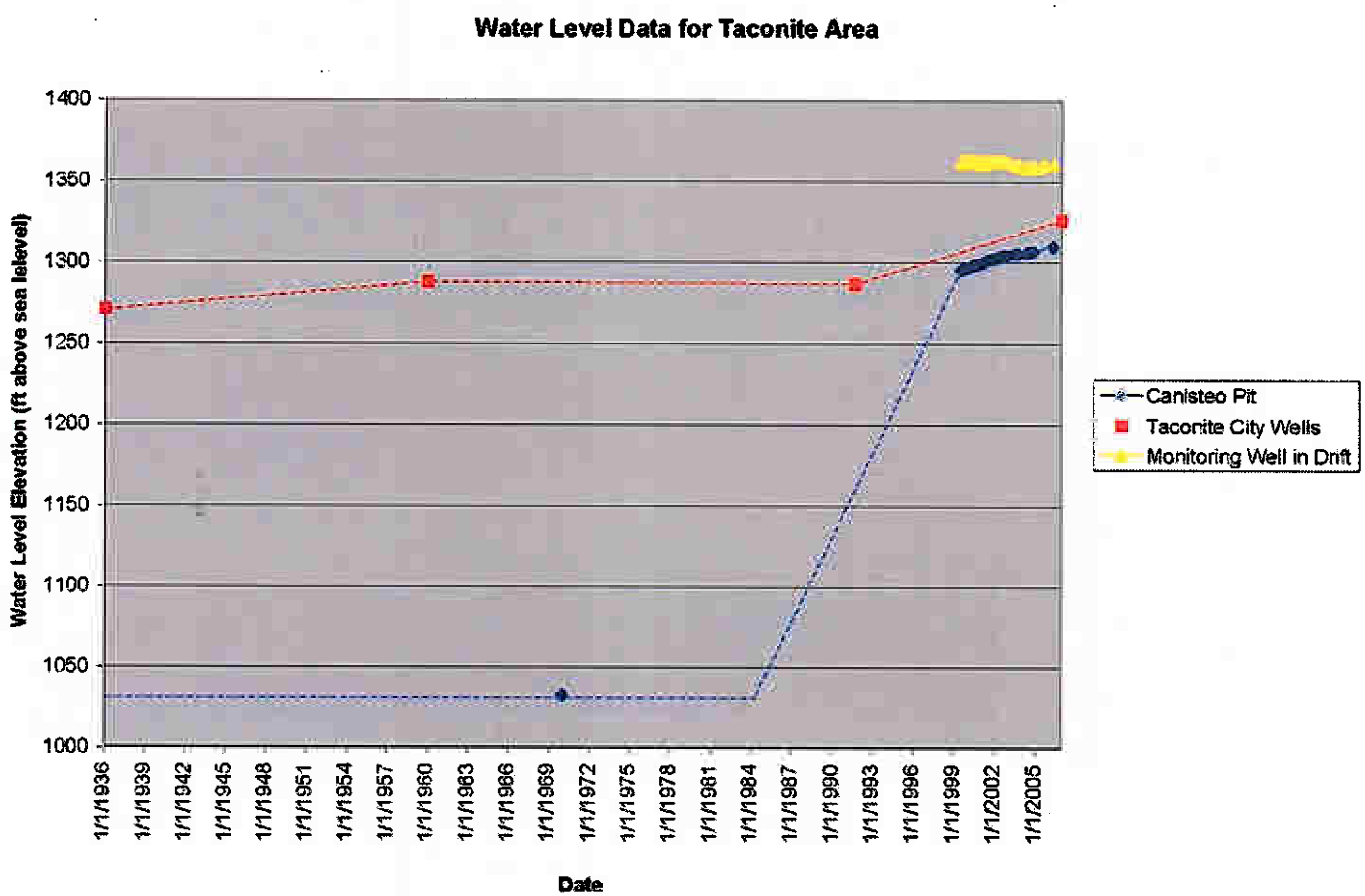

Figure 7. Graph of historic water level data for the Taconite area. Historic pit water level data is from Oakes (1970) and well water data is from 1) well construction records, and 2) Cotter and others (1965). Points represent actual data, whereas dashed lines represent the author's estimates.

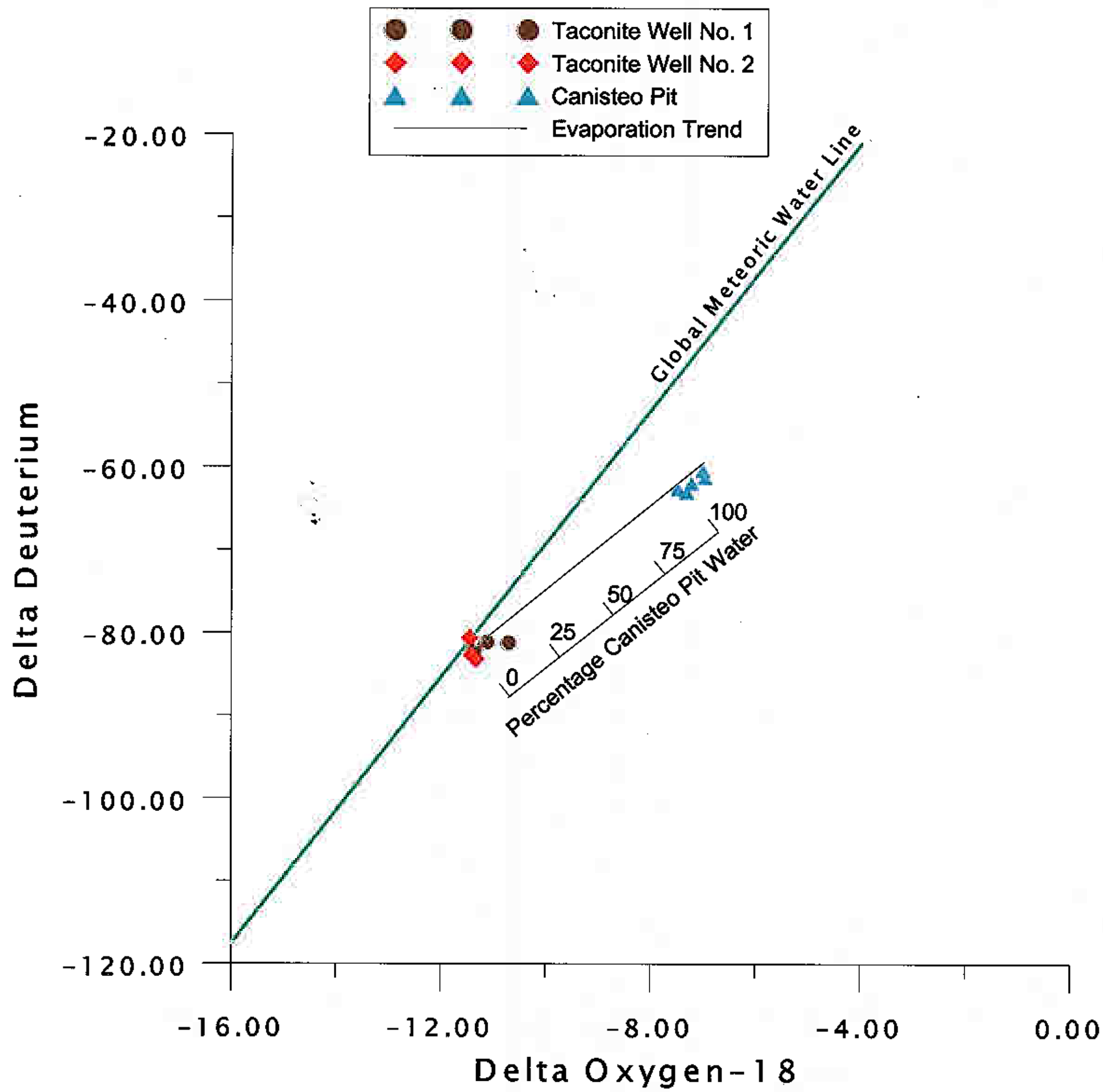

Figure 8. Stable isotopes of water.

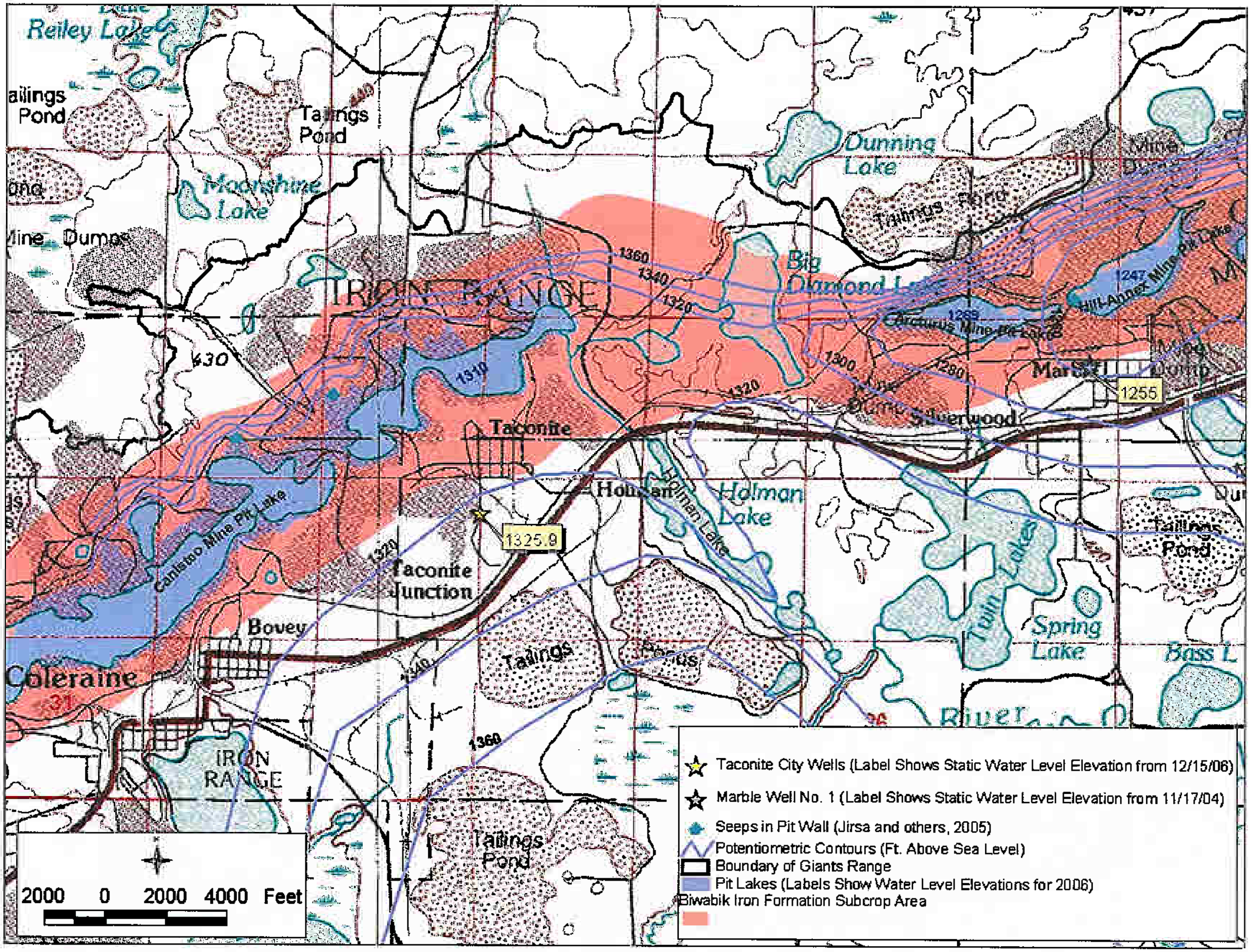

Figure 9. Groundwater flow direction in the Taconite area.

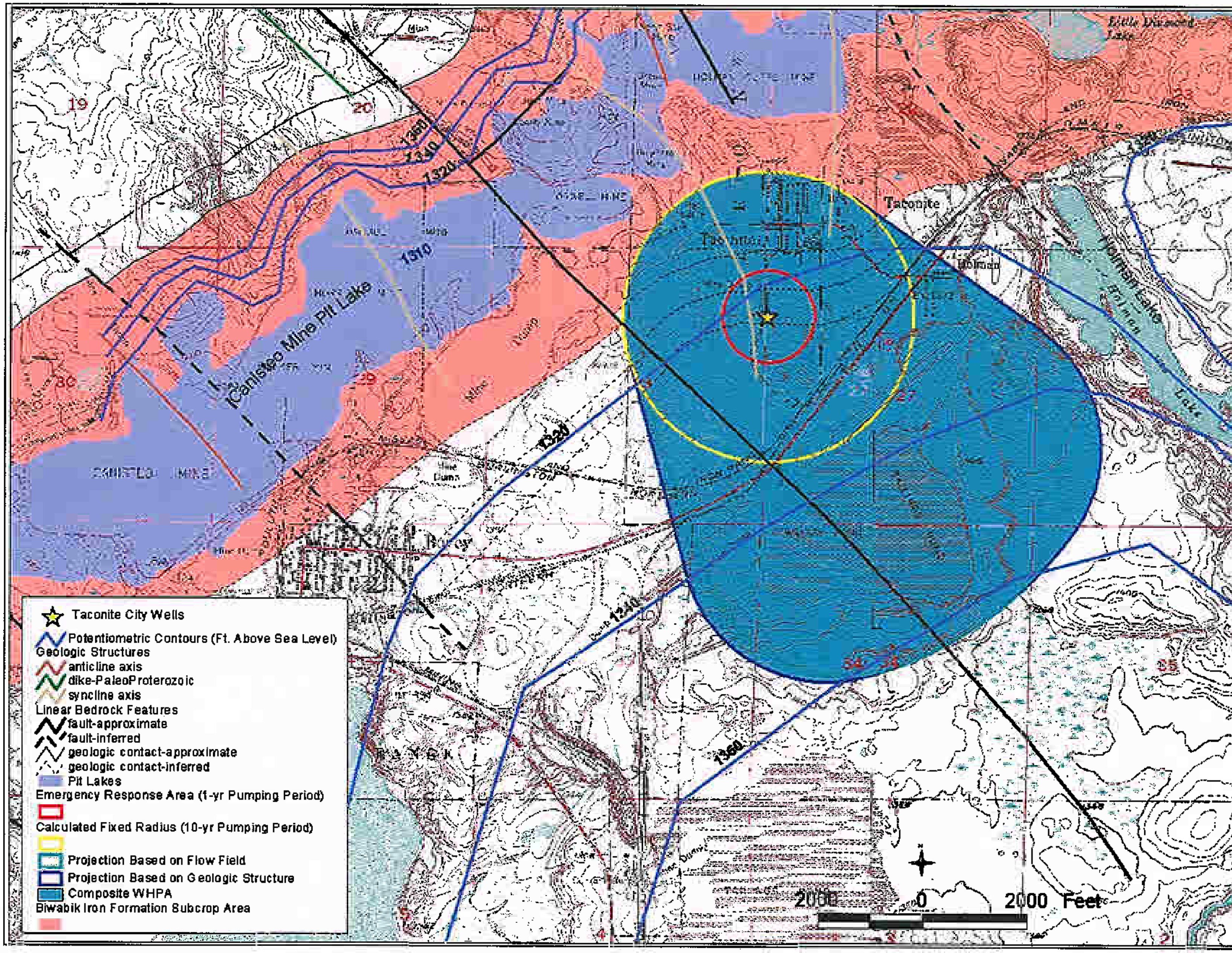

Figure 10. WHPA delineation procedure.

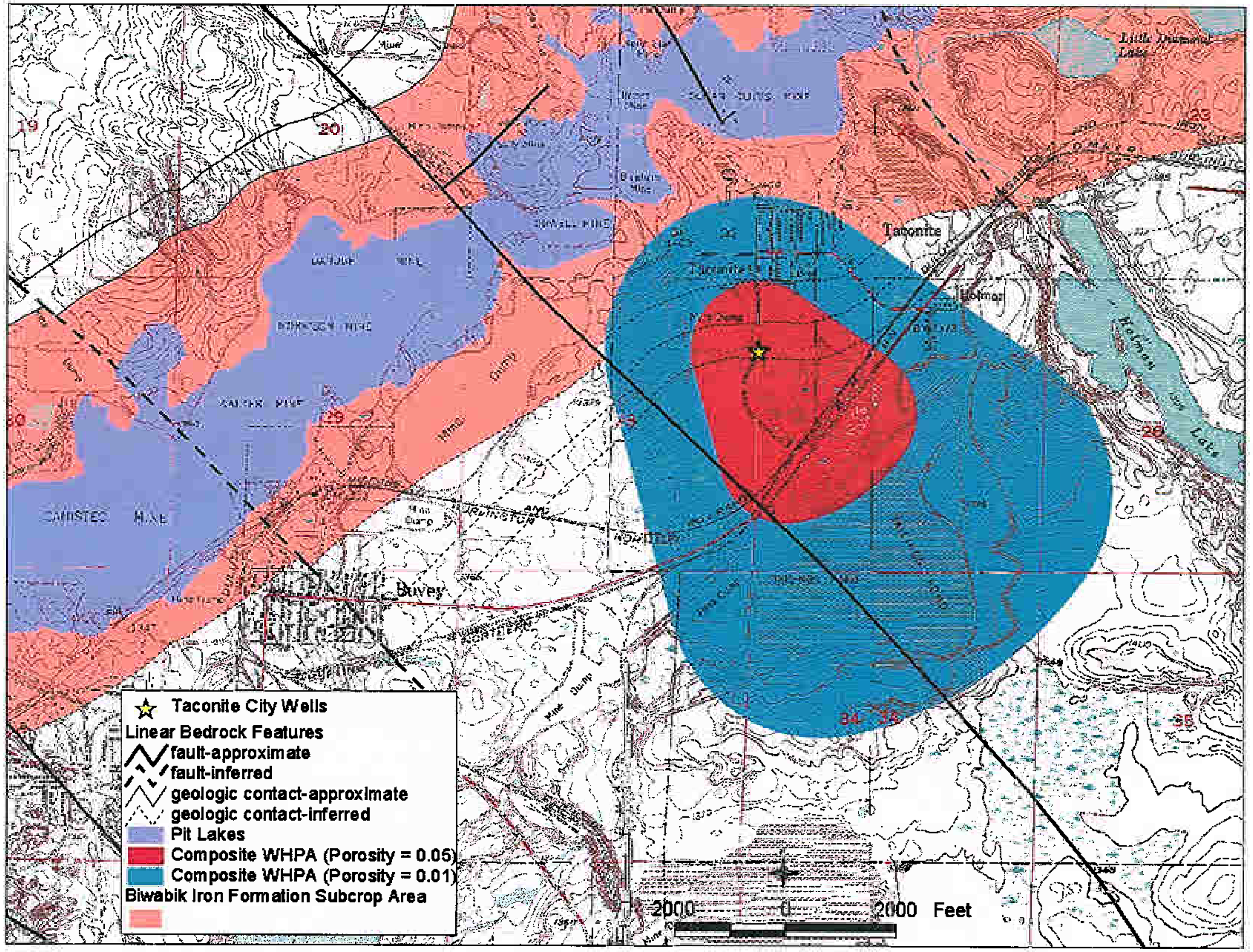

Figure 11. Sensitivity of the WHPA to aquifer porosity.

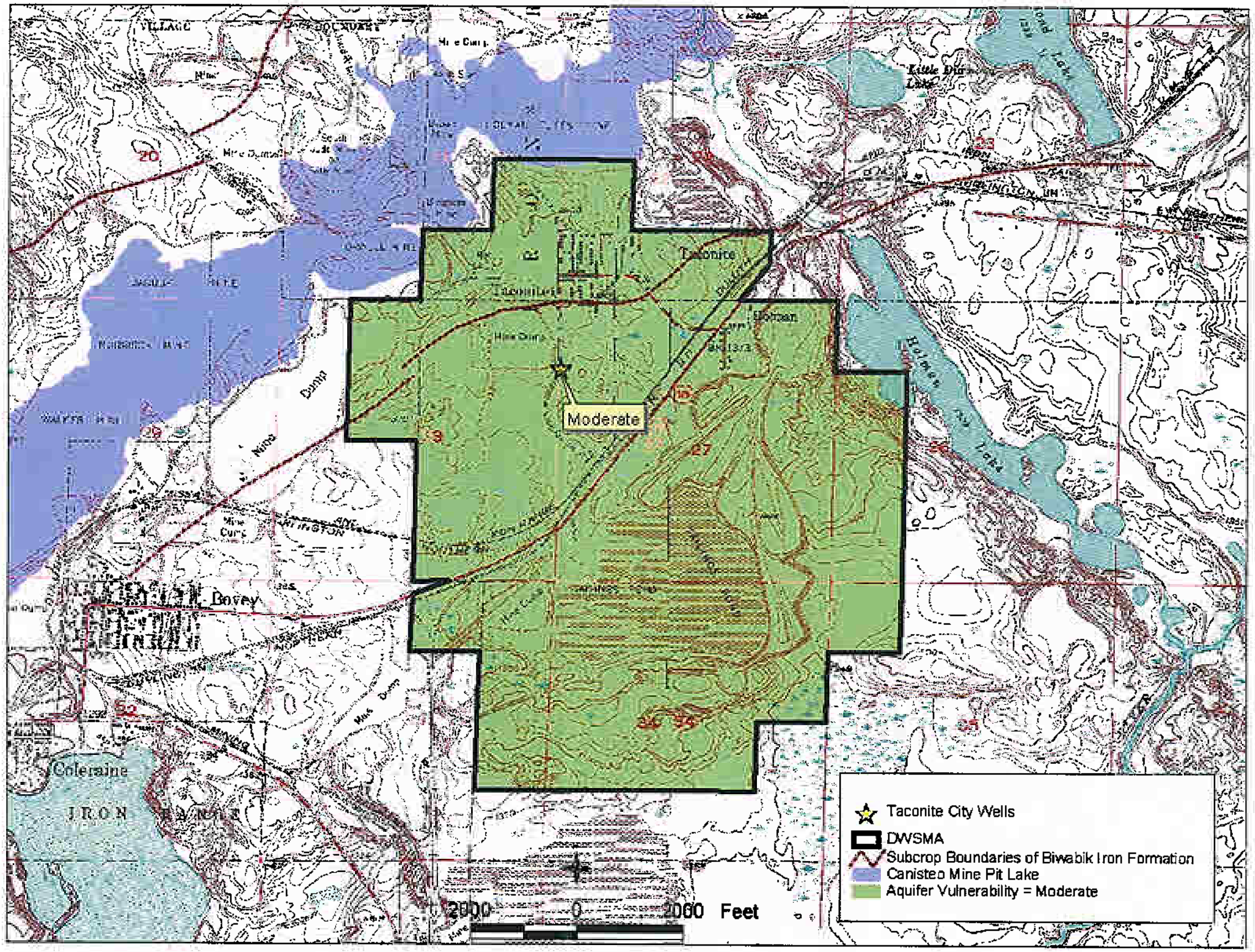

Figure 12. Vulnerability of the aquifer throughout the DWSMA.

Appendix III

Method Used to Estimate Transmissivity from Specific Capacity

Method Used to Estimate Transmissivity

The method used to estimate transmissivity from specific capacity data is similar to that of Bradbury and Rotheschild, 1985, and Mace (2000) but with some differences. The method is described in some detail here.

Starting with a rearrangement of Sternberg's (1973) equation that relates specific capacity (Sc) to transmissivity (T), the duration of pumping (t) the well radius (r_w)and storativity (S) for a partially penetrating well:

$$Sc = \frac{4\pi T}{\left[\ln\left(\frac{2.25\,T\,t}{r_w^2\,S}\right) + 2\,s_p\right]} \qquad \mathbf{1}$$

where s_p is the partial penetration factor defined base on the physical properties of the well and aquifer, L is the length of the screen portion of the aquifer and H is the aquifer thickness Brons and Marting (1961):

$$s_p = \frac{1-\left(L/H\right)}{\left(L/H\right)}\left[\ln\left(H/r_w\right) - G\left(L/H\right)\right] \qquad \mathbf{2}$$

Where the function G is approximated by Bradbury and Rothschild (1985) using the following polynomial with 0.992 correlation coefficient:

$$G\left(L/H\right) = 2.948 - 7.363\left(L/H\right) + 11.447\left(L/H\right)^2 - 4.675\left(L/H\right)^3 \qquad \mathbf{3}$$

Rearranging Equation 1 to solve for transmissivity and substituting for Sc in terms of the discharge of the well (Q) and the observed draw down at tine t (s), Sc=Q/s:

$$T = \frac{Q}{4\pi s}\left[\ln\left(\frac{2.25\,T\,t}{r_w^2\,S}\right)\right] + \frac{Q\,s_p}{2\pi s} \qquad \mathbf{4}$$

The second term in Equation 4 was solved directly from the draw down, discharge, well construction, and aquifer thickness information. The first term was solved iteratively with assumed values of storativity for confined (0.001) and unconfined (0.075) conditions.

References:

Bradbury, K.R., and Rothschild, E.R. (1985), *A computerized technique for estimating the hydraulic conductivity of aquifers from specific capacity data,* Ground Water, Vol. 23, No. 2, p. 240-246.

Brons, F., and Marting, V.E. (1961), *The effect of restricted fluid entry on well productivity,* Journal of Petroleum Technology, Vol. 13, No. 2, p. 172-174.

Sternberg, Y.M. (1973), *Efficiency of partially penetrating wells,* Ground Water, Vol. 11, No. 3, p. 5-7.